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Spatial and Temporal Efficiency in Climate Policy: Applications of *FUND*

RICHARD S.J. TOL
Vrije Universiteit, Institute for Environmental Studies, De Boelelaan 1115, 1081 HV Amsterdam, The Netherlands (e-mail: richard.tol@ivm.vu.nl)

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Abstract. *FUND* is an integrated assessment model of the interactions between climate and economy. Nine world regions emit greenhouse gases, and suffer damages from climate change. A number of greenhouse gas emission reduction policies are compared, including optimal and cost-effective strategies, strategies with early and late abatement, and strategies with and without international co-operation. The analyses confirm that co-operation matters, resulting in substantially lower costs or higher welfare. The real commitments of policy targets based on an absolute level (e.g., 1990 emissions) are hard to estimate because of the uncertainties in the baseline. Postponing action conflicts with minimising costs and maximising welfare, but so does sharp emission reduction at the short-term as proposed in the Kyoto Protocol.

Key words: climate change, emission reduction, efficiency, cost-effectiveness, equity

JEL classification: Q25, Q40

1. Introduction

Plans and advice for greenhouse gas emission reduction policy abound. The difference between well and not-so-well designed policies may be in costs of an order of magnitude higher. That difference is important since the sum of money involved are substantial, and stringent emission abatement is not universally accepted to be necessary. Keeping economic costs as low as possible thus increases political feasibility.

This paper looks at industrial carbon dioxide emission reduction strategies from the perspective of the temporal and, to a lesser extent, spatial allocation of abatement efforts. The experiments of the Energy Modeling Forum Round 14, Subgroup on Distribution of Costs and Benefits are run with the *FUND* model. In addition, a number of alternatives are analysed so as to spell out some of the consequences of the assumptions underlying the work of EMF14. Emission reduction profiles, net present costs, and their distribution over large regions are compared. There has been substantial discussion about desirable time profiles of emission reduction (cf. Azar and Rodhe 1997; Grubb 1997; Ramakrishna 1997; Wigley 1997; Wigley et al. 1996), but model-based analyses are scarcer than this discussion suggests

(Edmonds et al. 1997; Ha Duong et al. 1997; Manne and Richels 1996, 1997). Geographic distributions have received more thorough attention in the literature (see the surveys of Banuri et al. 1996; Fisher et al. 1996; Hourcade et al. 1996; Weyant et al. 1996), and therefore attract less attention in this contribution.

Although the paper speaks about issues high on the international, environmental policy agenda, results should be interpreted with greater than usual care. The political agenda reaches out to about 2015, and is mostly about emissions. The model used here reaches out to 2200, and is mostly about concentrations. The Kyoto Protocol talks about carbon sinks and non-CO_2 greenhouse gases. The model can only analyse reductions of industrial carbon dioxide emissions, for want of information of the costs of emission reduction for other gases, and for want of information about the costs of enhancing carbon sinks.

Section 2 describes the model, Section 3 the scenarios. Section 4 discusses the outcomes. Section 5 concludes.

2. The Model

The model used is version 1.6 of the *Climate Framework for Uncertainty, Negotiation and Distribution* (*FUND*).[1] Version 1.6 differs in a number of ways from version 1.5, which is described in Tol (1996, 1997a). The main differences between this and the previous versions are (i) the representations of atmosphere and climate, (ii) the costs of emission reduction, particularly in non-OECD regions, and (iii) the decision-making structure. Essentially, *FUND* consists of a set of exogenous scenarios and endogenous perturbations. The model is specified for nine major world-regions: OECD-America (excl. Mexico); OECD-Europe; OECD-Pacific (excl. South Korea); Central and Eastern Europe and the former Soviet Union; Middle East; Latin America; South and Southeast Asia; Centrally Planned Asia; and Africa. The model runs from 1950 to 2200, in time steps of a year. Some overlap with the observational record provides an opportunity for model validation. The prime reason for starting in 1950, however, is the necessity to initialise the climate change impact module. In *FUND*, climate impacts are assumed to depend on the impact of the year before, to reflect the process of adjustment to climate change. Thus, climate impacts are misrepresented in the first decades. This would bias optimal control if the first decades of the simulation coincided with the first decades of emission abatement. Similarly, the period 2100–2200 is there to provide the forward-looking agents in the 21st century for the proper time horizon. The calculated emission reductions in 2100–2200 have little meaning in and of themselves.

The *IMAGE* database (Batjes and Goldewijk 1994) is the basis for the calibration of the model to the period 1950–1990. Scenarios for the period 2010–2100 are based on the EMF Standardised Scenario. Note that the original EMF scenario had to be adjusted to fit *FUND*'s nine regions and yearly time-step. The period 1990–2010 is a linear interpolation between observations and the EMF scenario. The period 2100–2200 is an extrapolation of the EMF scenario. In addition, a library of alternative scenarios is available, consisting of the EMF Standardised Scenario (proper), and the IPCC IS92a, IS92d and IS92f scenarios (Leggett et al. 1992).

The scenarios concern the rate of population growth, urbanisation, economic growth, autonomous energy efficiency improvements, the rate of decarbonisation of the energy use (autonomous carbon efficiency improvements), and emissions of carbon dioxide from land use change, methane and nitrous oxide.

The scenarios of economic and population growth are perturbed by the impact of climate change. Population falls with climate change deaths, resulting from changes in heat stress, cold stress, malaria, and tropical cyclones. Heat and cold stress are assumed to affect only the elderly, non-reproductive population, so that the number of new births is not affected by heat and cold stress. The other sources of mortality do affect the number of births. Heat stress only affects urban population. The share of urban in total population is, up to 2025, based on the World Resources Databases; after 2025, urban population slowly converges to 95% of total population (comparable to present day Belgium or Kuwait); this is not varied between the scenarios. Population also changes with climate-induced migration between the regions. Immigrants are assumed to assimilate immediately and completely with the host population.

The tangible impacts of climate change are dead-weight losses to the economy. Consumption and investment are reduced, without changing the saving's rate. Climate change thus reduces long-term economic growth, although at the short-term consumption takes a deeper cut. Economic growth is also reduced by carbon dioxide emission abatement.

The energy intensity of the economy and the carbon intensity of the energy supply autonomously decrease over time. This process can be speeded up by abatement policies.

The endogenous parts of *FUND* consists of the atmospheric concentrations of carbon dioxide, methane and nitrous oxide, the global mean temperature, the impact of carbon dioxide emission reductions on economy and emissions, and the impact of the damages of climate change on the economy and the population.

Methane and nitrous oxide are taken up in the atmosphere, and then geometrically depleted:

$$C_t = C_{t-1} + \alpha E_t - \beta(C_{t-1} - C_{\text{pre}}) \tag{1}$$

where C denotes concentration, E emissions, t year, and pre pre-industrial. Table I displays the parameters for both gases.

The atmospheric concentration of carbon dioxide follows from a five-box model:[2]

$$\text{Box}_{i,t} = \rho_i \text{Box}_{i,t} + 0.000471\alpha_i E_t \tag{2a}$$

with

Table I. Paramters of equation (1).

Gas	α^{a}	β^{b}	Pre-industrial concentration
Methane (CH_4)	0.3597	1/8.6	790 ppb
Nitrous oxide (N_2O)	0.2079	1/120	285 ppb

[a] The parameter α translates emissions (in million metric tonnes of CH_4 or N_2O) into concentrations (in parts per billion by volume).
[b] The parameter β determines how fast concentrations return to their pre-industrial (and assumedly equilibrium) concentrations; $1/\beta$ is the atmospheric life-time (in years) of the gases.

Source: After Schimel et al. (1996).

$$C_t = \sum_{i=1}^{5} \alpha_i \mathrm{Box}_{i,t} \tag{2b}$$

where α_i denotes the fraction of emission E (in million metric tonnes of carbon) that is allocated to box i (0.13, 0.20, 0.32, 0.25 and 0.10, respectively) and ρ the decay-rate of the boxes (ρ = exp(−1/lifetime), with life-times infinity, 363, 74, 17 and 2 years, respectively). Thus, 13% of total emissions remains forever in the atmosphere, while 10% is – on average – removed in two years (after Hammitt et al. 1992). Carbon dioxide concentrations are measured in parts per million by volume.

Radiative forcing for carbon dioxide, methane and nitrous oxide are based on Shine et al. (1990). The global mean temperature T is governed by a geometric build-up to its equilibrium (determined by radiative forcing *RF*), with a life-time of 50 years. In the base case, global mean temperature rises in equilibrium by 2.5 °C for a doubling carbon dioxide equivalents, so:

$$T_t = \left(1 - \frac{1}{50}\right) T_{t-1} + \frac{1}{50} \frac{2.5}{6.3 \ln(2)} RF_t . \tag{3}$$

Global mean sea level is also geometric, with its equilibrium determined by the temperature and a life-time of 50 years. These life-times result from a calibration to the best guess temperature and sea level for the IS92a scenario of Kattenberg et al. (1996). *FUND* also calculates hurricane activity, winter precipitation, and winter storm activity because these feed into the damage module. However, these factors depend linearly on the global mean temperature. In the current model version, this is merely accounting; a future version of the model will improve on this. A future version will also include other greenhouse gases, and investigate the influence of sulphate aerosols (a regional climate effect).

The climate impact module is based on Tol (1996). A limited number of categories of the impact of climate change is considered: agriculture, sea level rise, heat and cold stress, malaria, tropical and extratropical storm, river floods, and unmanaged ecosystems. The damage module has two units of measurement: people and money.

People can die (heat stress, malaria, tropical cyclones), not die (cold stress), or migrate. These effects, like all impacts, are monetised. The value of a statistical life is set at \$250,000 plus 175 times the per capita income. The value of emigration is set at 3 times the per capita income, the value of immigration at 40% of the per capita income in the host region.

Other impact categories are directly expressed in money, without an intermediate layer of impacts measured in their 'natural' units.

Damage can be due to either the rate of change (benchmarked at 0.04 °C/yr) or the level of change (benchmark at 2.5 °C). Benchmark estimates are displayed in Table II. Damage in the rate of temperature change slowly fades at a speed indicated in Table III. Damage is calculated through a second-order polynomial in climatic change. Thus, damage D_t in year t is either

$$D_t = \alpha_t W_t + \beta_t W_t^2 \tag{4a}$$

or

$$D_t = \alpha_t \Delta W_t + \beta_t \Delta W_t^2 + \rho D_{t-1} \tag{4b}$$

with W the appropriate climate variable (temperature, sea level, hurricane activity, etc.) and α, β and ρ parameters.

Damage is distinguished between tangible (market) and intangible (non-market) effects. Tangible damages affect investment and consumption; through investment, economic growth is affected; through consumption, welfare is affected. Intangible damages effect welfare.

Relative vulnerability to climate change – α and β in (4) – is a function of economic development in many ways. The importance of agriculture falls with economic growth. The share of agriculture in total output changes with per capita income with an elasticity of 0.31, which corresponds to the per capita income elasticity across *FUND*'s 9 regions in 1990. Malaria incidence and the inclination to migrate fall logistically with increases in per capita income. Heat stress increases linearly with urbanisation. The valuation of intangible impacts increases logistically with per capita income.

Emission abatement is restricted to industrial sources of carbon dioxide. The costs of carbon dioxide emission reduction are calibrated to the survey results of Hourcade et al. (1996), supplemented with results of Rose and Stevens (1993) for developing countries. Regional and global average cost estimates, and their standard deviations result. Regional relative costs are shrunk to the global average, that is, the weighted average of the regional and global average is taken, with the inverse variances as weights. This reduces the influence of a single study. It particularly influences the developing regions, for which much less information on emission abatement costs is available. Costs are represented by a quadratic function. Table

Table II. Monetized estimates of the impact of global warming (in 10^9 US$ per year).

Region	Species	Life	Agric.	Sea	Extreme	Total
Level (temperature: +2.5 °C; sea level + 50 cm; hurricane activity: + 2.5%; winter precipitation: + 10%; extratropical storm intensity: +10%)						
OECD-A	0.0	−1.0	−5.3	0.9	2.5	−2.9
OECD-E	0.0	−1.0	−6.0	0.3	0.3	−6.5
OECD-P	0.0	−0.5	−6.1	1.5	5.5	0.3
CEE&fSU	0.0	3.7	−23.2	0.1	0.2	−19.1
ME	0.0	3.5	3.1	0.1	0.0	6.6
LA	0.0	67.0	7.3	0.2	0.0	74.5
S&SEA	0.0	81.4	15.8	0.2	0.6	98.8
CPA	0.0	58.4	−22.2	0.0	0.1	36.3
AFR	0.0	22.5	5.4	0.1	0.0	28.0
Rate (temperature: 0.04 °C/year; other variables follow)						
OECD-A	0.3	0.2	0.3	0.2	0.2	1.2
OECD-E	0.3	0.2	0.0	0.2	0.0	0.7
OECD-P	0.2	0.1	0.0	0.3	0.4	1.0
CEE&fSU	0.1	0.1	0.0	0.0	0.0	0.2
ME	0.0	0.0	0.1	0.0	0.0	0.2
LA	0.0	0.4	0.1	0.1	0.0	0.6
S&SEA	0.0	0.3	0.1	0.1	0.0	0.6
CPA	0.0	0.2	0.3	0.0	0.0	0.5
AFR	0.0	0.0	0.1	0.0	0.0	0.2

Source: Tol (1996).

Table III. Duration of damage memory per category.[a]

Category	Years	Category	Years
Species loss	100	Immigration	5
Agriculture	10	Emigration	5
Coastal protection	50	Wetland (tangible)	10
Life loss	15	Wetland (intangible)	50
Tropical cyclones	5	Dryland	50

[a] Damage is assumed to decline geometrically at a rate of 1 − 1/life-time.

Source: Tol (1996).

Table IV. Parameters of the CO_2 emission reduction cost function.[a]

OECD-A	2.0789	CEE&fSU	2.0488	S&SEA	2.1268
OECD-E	2.3153	ME	2.1041	CPA	1.9544
OECD-P	2.2171	LA	2.1253	AFR	2.0931

[a] The proportional loss of GDP C in year t of proportional emission reduction R in year t follows: $C_t = \alpha R_t^2$. The costs of GDP are modelled as a dead-weight loss to the economy. Emission reduction is brought about by a permanent shift in energy- and carbon-intensity.

Source: After Hourcade et al. (1996) and Rose and Stevens (1993).

IV presents the parameters. Roughly, a 1% cut in emissions costs 0.02% of GDP; a 10% cut costs 2%.

In *FUND*, each region has its own decision maker. *FUND* 1.6 also distinguishes generations of decision makers (rather than a single one as in previous versions and other models). Each decision maker has control over a ten-year period only, but does optimise the net present welfare of her region from the start of the control period up to 2200. Each decision maker knows the emission reduction efforts of all decision makers in all regions at all times. The equilibrium is found iteratively; without co-operation between regions, convergence is rapid (i.e., 4 or 5 iterations); with global co-operation, convergence is much slower (i.e., over 10 iterations). The distinction between generations of decision makers has two implications. Firstly, in a cost-benefit analysis, a decision-maker not only has to match her decisions with those of other regions, but also with the decisions of other generations. Secondly, the definition of intertemporal cost-effectiveness vanishes, as there is no decision-maker controlling the entire time-period. Explicitly distinguishing generations of decision makers recognises the sovereignty of each generation. In a cost-benefit analysis, this implies that emission reductions are individually rational at all times. Collective decision-making over generations and targeted capital transfers between generations are impossible in the model as in reality. Cost-effectiveness also implicitly assumes that targeted integenerational capital transfers are possible (such transfers are needed to make an actual Parteo improvement of a potential one). In addition, cost-effectiveness analysis is usually biased towards the first period (unless the pure rate of time preference is zero).

3. Experimental Design

A number of experimental runs with *FUND* 1.6 are compared here. These are listed and described below. Results are discussed in the next section.

Business as usual: No emission reduction policy is implemented in any region at any time.

Non-co-operative optimum: Emission reduction is such that each region and each generation optimises its net present welfare, with perfect knowledge of the optimal actions of other regions and generations.

Co-operative optimum: Emission reduction is such that each generation optimises its net present welfare (i.e., the sum of the regional welfares), with perfect knowledge of the optimal actions of other generations.

EMF14: The next 12 experiments are interpretations of the modelling comparison exercises of EMF14. Three stabilisation targets for the atmospheric concentration of carbon dioxide are considered: 450 ppm, 550 ppm and 650 ppm. These are translated to global emission constraints by EMF14 according to two time profiles: WRE and WGI (cf. Wigley et al. 1996). The former emission profile follows the business as usual scenario longer than does the second. Emission reductions can be implemented either as regional targets or as global targets (i.e., full international cooperation; this resembles EMF14's case with international trade in emission permits, but without the economic ramifications of the associated international capital flows). The experiments are denoted by time profile, target and co-operation; for example, *WRE550NC* denotes the WRE time profile towards 550 ppm, implemented without international co-operation. In the non-cooperative case, for a stabilisation target of 550 ppm, developing regions do not implement emission abatement policies before 2030. During the period 1990–2030, Annex I regions (i.e., the OECD plus Central and Eastern Europe and the former Soviet Union) each reduce their emissions with the same proportion so as to meet the global emission constraint.[3] After 2050, each region is allocated emissions proportional to their 1990 population so as to meet the global target. Between 2030 and 2050, emission entitlements shift linearly from the former to the latter scheme. The sum of regional emission constraints lies slightly under the global emission constraint according to EMF; for a number of regions, particularly South and Southeast Asia and Africa, the regional constraint lies well above business as usual emissions. For the 450 ppm stabilisation target, dates are shifted forwards by 10 years; for the 650 target, backwards by 10 years. In the co-operative case, developing regions do not abate emissions before 2020 (450 ppm), 2030 (550 ppm) or 2040 (650 ppm); regional emissions are set so as to maximise global welfare while meeting the global constraint.

WRE550P: This scenario is the same as *WRE550NC* but that the current rather than the 1990 population is used to allocate emissions amongst regions.

WRE550x: These scenarios are the same as *WRE550NC* but that the scenarios for population, economy and technology are different. The basic scenario is *FUND*'s. Alternative scenarios are IS92a (*WRE550a*), EMF Standardised (*e*), IS92d (*d*) and IS92f (*f*). Note that IS92a, EMF Standardised and *FUND*'s basis scenario are very close to one another.

WRE550CBA: This scenario is the same as *WRE550NC* but that regions also reduce greenhouse gas emissions if that improves their welfare. Optimisation is non-co-operative.

CEA550NC: This scenario is based on *WRE550NC*. Emission reduction profiles are different so as to lower the net present costs of abatement (for the world as well as for the regions) while keeping concentrations below 550 ppm. This is not a real-cost-effectiveness analysis, because global net present abatement costs do not reflect the interest of the agents in the model and side payments across regions and generations are not allowed. In addition, a full-fledged cost-minimisation algorithm was not used. Note that either Wigley et al. (1996) nor Ha Duong et al. (1997) minimise costs. Both analyses compare a fixed set of scenarios (the EMF scenarios above). Manne and Richels (1996, 1997) do perform a real cost-effectiveness analysis, with similar results as *FUND* (see below).

KYOTO: Two scenarios, based on *CEA550NC*, are added as a preliminary evaluation of the agreements made at the 3rd Conference of the Parties to the UN Framework Convention on Climate Change in December 1997 in Kyoto. In these scenarios, OECD-America reduces its industrial CO_2 emissions in 2010 to 93% of its 1990 emissions; OECD-Europe reduces its emissions to 92%; and OECD-Pacific reduces its emissions to 94%.[4] The targets chosen are those of the USA, the European Union, and Japan, respectively. The Kyoto Protocol has 2012 as its target year. The Kyoto Protocol covers all sources and sinks of carbon dioxide, as well as a range of other greenhouse gases. The current version of *FUND* cannot analyse this. In the first *KYOTO* scenario, emission reduction is as above to 2010, and then according to the principles of *CEA550NC* for 2010–2200. In the second *KYOTO* scenario, emission reduction is as above to 2010, then frozen until it meets *CEA550NC*, and then according to *CEA550NC*.

4. Results

Figure 1 displays six global emission trajectories for the period 1990–2100. The business as usual scenario assumes increasing emissions. Welfare optimisation does not alter this. Without international co-operation, optimal emissions are even hard to distinguish from no-control emissions. The WGI550 stabilisation trajectory implies an immediate deviation from business as usual, how drastically so depend on the ambition of the stabilisation goals. The WRE550 stabilising trajectory follows business as usual until 2020 (2010 for WRE450; 2030 for WRE650) and then sharply bend away. The “cost-effective” trajectory (towards 550 ppm) implies a smooth transition. The first “Kyoto” trajectory is also smooth, but significantly deviates earlier. Table V displays CO_2 emissions in 2010 as percentage deviation from 1990 for the world and three major blocks of nations. The initial political aims of the countries of the European Union (stabilisation at minus 15% by 2010 compared to 1990) roughly coincide with the *WGI550* trajectory. The Kyoto protocol speaks of −8%, which lies somewhere between *WGI550* and *WGI650*.

Initial WRE emissions are too high from a welfare maximising point to view, both with and without international co-operation (cf. Nordhaus 1994; Nordhaus and Yang 1996; Schneider and Goulder 1997). The *WRE550CBA* scenario (not

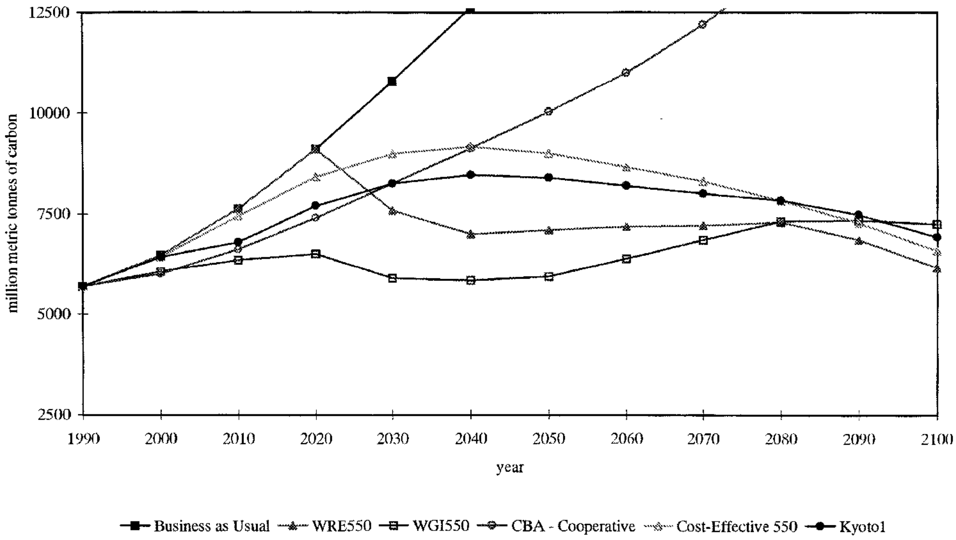

Figure 1. Global emissions of industrial carbon dioxide for the period 1990–2100 for the business as usual and five alternative policy scenarios.

Table V. Emissions in 2010 as percentage deviation from 1990 levels.[a]

Scenario	OECD	CEE&fSU	LDCs	World
Business as usual	+16.8	+28.2	+70.7	+33.9
'Kyoto'	−0.8	+3.7	+69.6	+19.2
Non-co-operative optimum	+15.8	+28.2	+69.0	+32.9
Co-operative optimum	+1.2	+4.5	+53.0	+16.0
WRE450/550/650	+16.8	+28.2	+70.7	+33.9
WGI450	−27.8	+19.7	+70.7	+0.8
WGI550	−13.8	−4.1	+70.7	+11.3
WGI650	+3.8	+11.7	+70.7	+20.0
'Cost-effective'	+12.7	+23.8	+69.6	+30.6

[a] Emissions of industrial CO_2 in 1990 and 2010 according to *FUND*.

Source: Own calculations.

displayed) roughly follows the non-co-operative optimal trajectory until 2020 when it starts roughly following *WRE550NC*. The "cost-effective" trajectory also implies emissions lower than business as usual right from the start. This indicates that the economically preferred option is to start slowly but right away with greenhouse gas emission abatement. This would also allow time to decide whether a stabilisation or an optimisation framework is appropriate, and to establish international co-operation. In any case, the marginal damage costs of emissions are likely to be greater

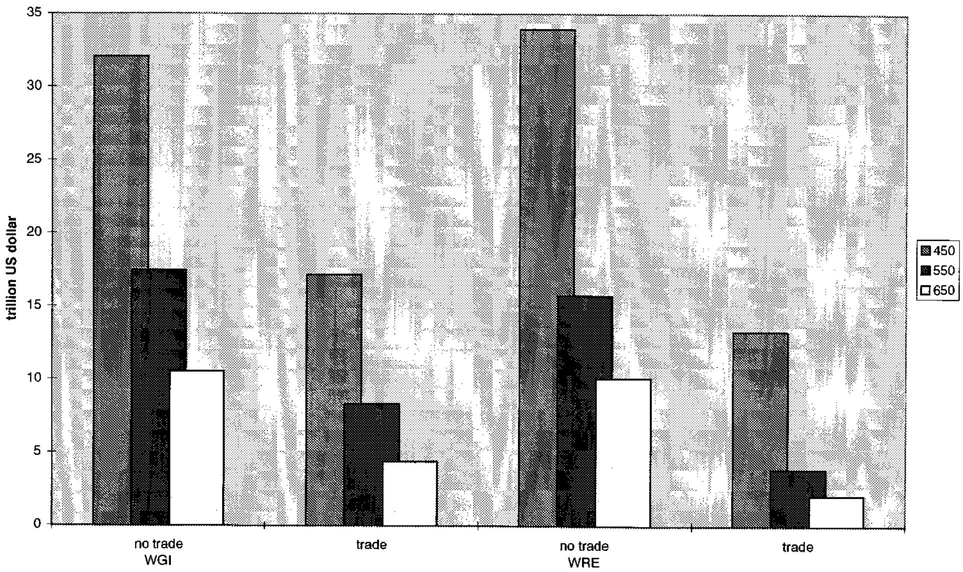

Figure 2. Net present costs of emission reduction of three alternative stabilisation targets, two alternative trajectories, and with and without international trade in emission permits.

than zero (cf. Pearce et al. 1996) and so is the current shadow price of a future emission constraint (cf. Manne and Richels 1996, 1997).

Figure 2 depicts the costs of the WGI and WRE stabilisation trajectories, expressed as the net present value (through 2050, using a 5% discount rate) of the consumption losses due to emission abatement and the consumption gains due to reduced climatic change. Obviously, the more ambitious the target, the higher the costs. In contrast to earlier findings (Weyant 1997a, b), the difference in costs between WGI and WRE is not that large. WGI is even slightly cheaper for the 450 ppm target.

The reasons have to do with structural differences between *FUND* and, say, *MERGE*. In *FUND*, emission reductions lead to a permanent shift in technology, away from energy- and carbon-intensive production and consumption. Early emission reductions make later emission constraints cheaper. The decision-makers do not care about the costs of emission reduction their successors face (except of course of its influence on their own marginal costs and benefits). An alternative interpretation is that *FUND*'s agents are myopic (or have little faith in governments enforcing long-term plans), so that rapid action always comes unexpected and hence at a large cost. This conclusion is shared by Ha Duong et al. (1997), although sharp emission reduction is of course also expensive in the near future (probably even more so because of technological change) while being less effective (because of the carbon cycle). The high costs of sharp emission reduction combined with a baseline that differs from other models' baselines,[5] leads to emission reduction efforts that are very different for different generations, for both WGI and WRE.

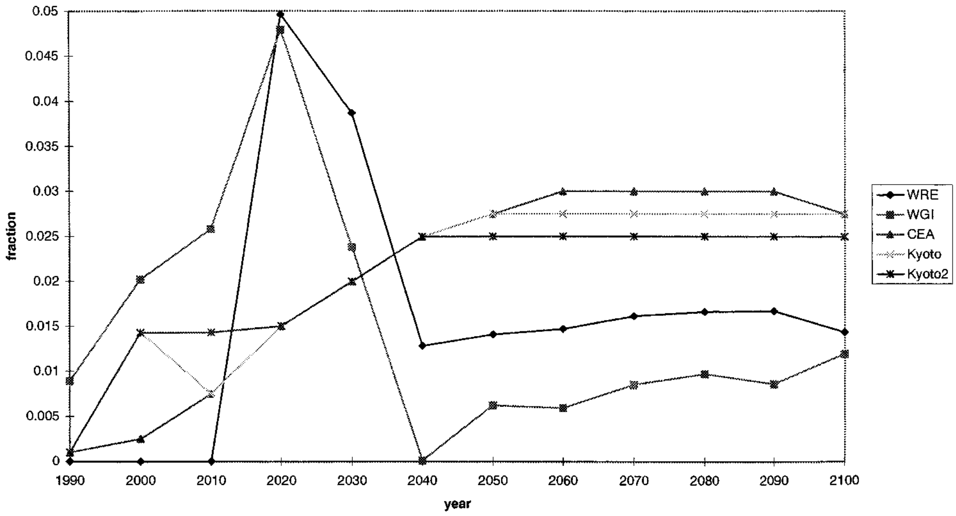

Figure 3. Emission reduciton effort of OECD-Europe according to five alternative policy scenarios.

Equity considerations apart, the non-linearity of costs in abatement implies that the additional costs of one generation are higher than the cost savings of another. Figure 3 shows the bumpy emissions reduction profile for OECD-Europe for the WRE and WGI (non-cooperative) trajectories towards stabilisation at 550 ppm. Marginal costs are roughly proportional to the abatement effort. Direct costs are roughly quadratic in abatement. Figure 3 also shows the 'cost-effective' trajectory, which is much smoother. Net present costs of this path are about 6 trillion dollars, compared to about 15 trillion for the other two. The amount of 6 trillion dollars is comparable though somewhat lower than the findings of *MERGE*, *MiniCAM*, *CETA*, *SGM* and *WorldScan* (cf. Weyant, 1997a, b). Note that the models are calibrated to the same sources.

Figure 3 also shows a 'cost-effective' strategy that complies to Kyoto ('Kyoto'). Emission reductions up to 2010 are substantially higher – in fact, close to *WGI550NC* – in return for which emission reduction in the later years can be somewhat lower. The next present costs for the whole world increase by about 1 trillion dollars to 7 trillion dollars. If the 'bumpiness' of scenarios is removed ('Kyoto2'), net present costs increase by another half a trillion dollars.

The results above are based on only one scenario, *FUND*'s base scenarios. Figure 4 displays global emission reduction, relative to alternative baselines, for the *FUND*, IS92a, IS92d, IS92f and EMF scenarios. Note that the EMF and *FUND* scenarios are higher than IS92a, and EMF even higher than IS92f. The *FUND* scenario is a bit peculiar, as emissions only start to deviate from baseline in 2020. On the other hand, the *FUND* scenario is, for the period 1990–2010, better in line with the observations over the period 1950–1990 than any other scenario. The differences between the scenarios are profound. In 2000, the maximum difference

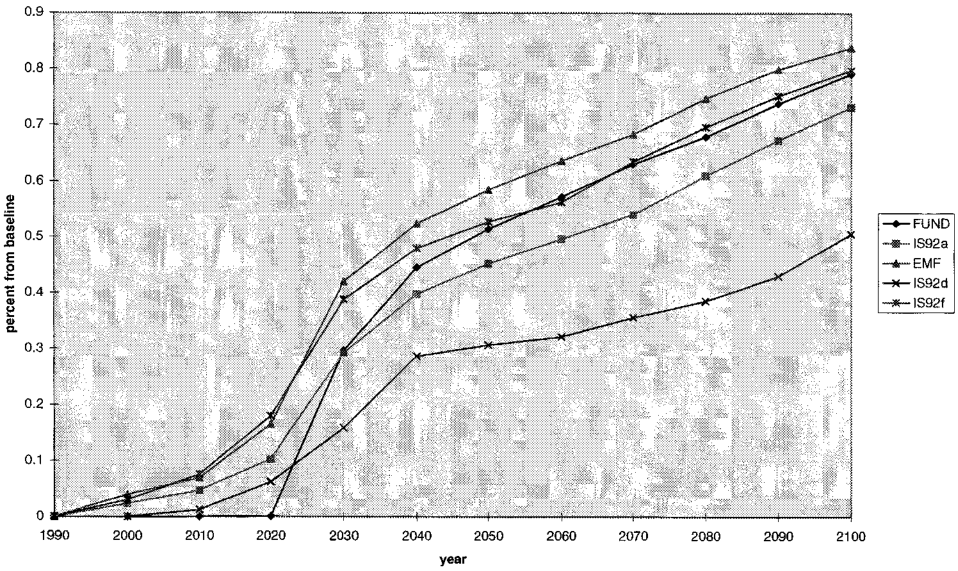

Figure 4. Global emission reduction effort for five alternative baseline scenarios and one policy scenario (WRE550nc).

is 4%, in 2010 8%, in 2020 18% and then increasing to 37% in 2090. Emission reduction costs of policies based on an absolute baseline (1990 emissions) may thus differ substantially with the reference scenario.

The *WRE550P* deviates from the EMF experiments in that current rather than 1990 population is used to allocate emissions. Obviously, the Annex I regions are worse off than under *WRE550NC* as their share in the global population declines over time. The same goes, however, for China and Latin America so that the gains for the non-Annex region as a whole is insubstantial. The OECD gains sufficiently to compensate the losing regions, that is, the Middle East, South and South-east Asia and Africa (cf. Table VI). This indicates that the choice of 1990 populations as the basis for emission allocation is not bad, considering the difficulties with reliable and agreed population projections.

5. Conclusions

It is possible to stabilise atmospheric concentrations of carbon dioxide at an acceptable cost. However, comparing stabilisation scenarios, even the 'cost-effective' ones, with optimisation scenarios reveals stabilising atmospheric concentrations is not justified on the basis of welfare-maximisation. Should policy makers nevertheless decide to pursue stabilisation, then the design of the emission reduction strategy becomes very important. A strategy based on absolute numbers may prove very costly. This follows from comparing the WRE 'cost-effective' solution with *FUND*'s. The logic of WRE does not apply to *FUND*, so that a single target (keep

Table VI. Net present costs of emission reduction for *FUND*'s 9 regions compared for *WRE550NC* and *WRE550P* (billion US dollar; discount rate: 5%).

Region	*WRE550NC*	*WRE550P*	Difference
OECD-America	4,834	6,669	1,835
OECD-Europe	2,514	4,515	2,001
OECD-Pacific	2,471	3,205	734
Central and Eastern Europe and the former Soviet Union	5,071	7,162	2,091
Middle East	223	102	−113
Latin America	93	105	12
South and South-east Asia	−16	−63	−47
China	614	814	200
Africa	−43	−78	−36
OECD	10,108	13,172	3,063
Central and Eastern Europe and the former Soviet Union	5,071	7,162	2,091
Less developed countries	871	887	16
World	15,762	22,438	6,676

Source: Own calculations.

concentrations below this level) is translated into a multitude of targets (keep emissions in this region at that time below such level), dramatically increasing costs. The same would happen if *FUND*'s solution would be transposed to another model, or the real world. A similar phenomenon is observed when the baseline scenario changes: emission reduction efforts and costs differ, also in a qualitative way, if we end up on a different development path than anticipated. Therefore, given the uncertainties about the future, agreeing to absolute target, e.g., emissions relative to 1990 levels, may well lead to emission abatement stricter than agreed to, or more lenient than intended. Since action is to be taken and progress to be reviewed by sovereign states and their successive governments, agreements may crumble under unrealised expectations. A better way forward, albeit harder to initially negotiate, is a mechanism for adaptive control, in which targets and instruments are constantly reviewed as new scientific results emerge and empirical findings accumulate (cf. Rayner and Malone 1997).

A second feature that arise from the experiments reported here is that *FUND* does not support the conclusion that it is better to postpone emission reduction a couple of decades. Indeed, welfare-maximisation advises early abatement, although modest. Similarly, the 'cost-effective' solution of *FUND* starts controlling emissions in the first decade, although again modestly so. This is in agreement with the theoretical findings of Tol (1997a), using a differently structured model. *FUND* does support, however, that drastic emission reduction at the short-term is a bad idea. In fact, drastic emission reduction is bad at any time (for political reasons and because of costs). A smooth trajectory of abatement is much cheaper, and will achieve similar concentrations.

Notes

1. The source code of the model is available upon request. The model is implemented in TurboPascal 7.0 and operates under DOS and Windows.
2. Note that the boxes do not represent identifiable subsystems of the carbon cycle; instead, the boxes are mathematical abstractions, as the model is a reduced-form version of a more complex carbon cycle model.
3. This scenario was designed well before the emission target differentiation of the Kyoto Protocol (which is small for the major players). In the cooperative cases, differentiation is allowed, based on cost-minimisation.
4. Recall that *FUND*'s 1990 baseline slightly deviates from observations. The reductions are relative to the EMF emission data for 1990.
5. Note that the global or regional emission allotments are not necessarily fully used. Since the carbon cycle model also differs, atmospheric concentrations in *FUND* differ from their targets.

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